Optical Counterpart of The Ultraluminous X-ray Source NGC 1313 X-2

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We present new optical and *Chandra* observations of the field containing the ultraluminous X-ray source NGC1313 X-2. On an ESO 3.6 m image, the *Chandra* error box embraces a $R = 21.6$ mag stellar-like object and excludes a previously proposed optical counterpart. The resulting X-ray/optical flux ratio of NGC 1313 X-2 is ~ 500. The value of f_X/f_{opt}, the X-ray variability history and spectral distribution indicate a luminous X-ray binary in NGC 1313 as a likely explanation for NGC 1313 X-2. The inferred optical luminosity ($L \approx 10^5 L_\odot$) is consistent with that of a $\approx 10 M_\odot$ companion.

1. INTRODUCTION

Point-like, off-nuclear X-ray sources with luminosities significantly exceeding the Eddington limit for one solar mass are being progressively discovered in the field of many nearby galaxies (e.g. [5]). These powerful objects, commonly referred to as ultraluminous X-ray sources (ULXs), do not appear to have an obvious Galactic counterpart. Despite some of them have been identified with supernovae or background active galactic nuclei, the nature of most of these sources remains unclear. Among the various possibilities, the most favored explanation is that ULXs are powered by accretion and that they are somewhat special X-ray binaries, either containing an intermediate mass black hole (BH) with $M_{BH} \geq 100\, M_\odot$ (see e.g. [4,12]) or having beamed emission toward us (see e.g. [13]). For a recent review on the properties of ULXs we refer to [8]. Optical observations are of fundamental importance to better assess the nature of these sources but they are still rather scarce (see e.g. [3,9]). A certain number of ULXs have optical counterparts in the Digitized Sky Survey or Hubble Space Telescope images (e.g. NGC 5204 X-1 [17,10]) and some appear to be embedded in emission nebulae a few hundred parsecs in diameter [16].

NGC1313 X-2 was one of the first sources of this type to be found. It was serendipitously discovered in an *Einstein* IPC pointing toward the nearby SBc galaxy NGC 1313 [7]. Originally included in the *Einstein* Extended Medium Sensitivity Survey as MS 0317.7-6647, it is located $\sim 6'$ south of the nucleus of NGC 1313. Stocke et al. [21] performed multi-wavelength observations of MS 0317.7-6647, identified a possible optical counterpart and proposed that the source could be either a Galactic isolated neutron star or a binary containing a massive BH in NGC 1313. A very recent analysis of a *XMM* EPIC MOS observation of NGC 1313 [15] indicates that two spectral components, soft and hard, are required to fit the spectrum of NGC 1313 X-2 and that the normalization of the soft component yields $M_{BH} \geq 830 M_\odot$.

We present new optical[1] and *Chandra* observations of NGC 1313 X-2, with the aim to shed further light on its enigmatic nature[2].

[1]Based on observations collected at the European Southern Observatory, Chile, Program number 68.B-0083(A).

[2]Results reported in these Proceedings are based on new

2. X-RAY AND OPTICAL DATA

2.1. X-ray astrometry

NCG 1313 X-2 was observed by *Chandra* on 13 Oct 2002. The observation had a duration of 19.9 ks. The primary goal of the observation was to study sources near the center of the galaxy, but the aim-point was adjusted to also place NGC 1313 X-1, NGC 1313 X-2, and SN 1978K on the S3 chip of the ACIS-S. Data were extracted and subjected to standard processing and event screening. No strong background flares were found, so the entire observation was used. Because the source is $5'$ off axis, the point spread function was fitted with an ellipsoidal Gaussian ($1.9''$ along the major axis and $1.1''$ along the minor axis, rms values). Also, the pixel with the highest number of counts is offset by $0.8''$ from the center of the fitted ellipse. Taking these uncertainties into account, we conservatively estimate a positional error of $0.7''$ (1-σ). The final *Chandra* position is: α = 03h 18m 22.27s$\pm$0.12s, δ = -66^0 36$'$ 03.8$''\pm$0.7$''$.

In order to check the accuracy of the *Chandra* aspect solution, we exploited the presence in the field of view of a quite peculiar supernova, SN 1978K, that shows powerful radio and X-ray emission. The *Chandra* position of SN 1978K is α = 03h 17m 38.69s, δ = -66^0 33$'$ 03.6$''$ (J2000), within $0.46''$ from the accurate ($0.1''$) radio position of [19]. This is consistent with the expected *Chandra* aspect accuracy.

The position of NGC 1313 X-2 was previously determined from a *ROSAT* HRI [21,20] and a *XMM* EPIC-MOS [15] observation. Typical 1-σ error boxes for both instruments are $\sim 3''$ for *ROSAT* HRI and $\sim 2''$ for *XMM* EPIC-MOS. The *ROSAT* and *XMM* positions and corresponding error boxes are summarized in Table 1.

2.2. Optical astrometry and photometry

Optical images of the field of NGC1313 X-2 in the *R*-band (Bessel filter) were taken on 16 January 2002 with the 3.6 m telescope of the European Southern Observatory (ESO) at La Silla (Chile). We used EFOSC2 with a Loral/Lesser CCD of 2048$\times$2048 pixels yielding a field of view of $\sim 5' \times 5'$ at a resolution of $0.314''$/pixel (rebinned by a factor 2). The night was clear with a seeing of about $1''$. Four images were obtained for a total exposure time of 1320 s. Standard reduction of the data (including bias subtraction and flat-field correction) was performed within the IRAF (v 2.12) environment.

Our four ESO images were astrometrically calibrated using an IRAF task (PLTSOL) and performing a polynomial interpolation starting from the positions of GSC2 ESO field stars. The internal accuracy of this procedure was estimated comparing the actual positions of a number of GSC2 stars not used for astrometric calibration with the positions contained in the catalog. The accuracy is 0.3" (1-σ). The four calibrated images were then summed together and the resulting image is shown in Figure 1.

In order to check for the relative systematics between the optical and X-ray astrometric calibrations, we used the position of SN 1978K. This supernova is inside the *Chandra* field of view but outside our optical image. Thus, we analyzed also an archival image of SN 1978K (from the Padova-Asiago Supernova Archive) taken on 13 September 1999 with the same telescope and a similar instrumental set-up (ESO 3.6m+EFOSC/2.9+R#642, exposure time 180 s). After calibrating the archival image, the position of SN 1978K is α = 03h 17m 38.605s, δ = -66^0 33$'$ 03.13$''$ (J2000). This is within $0.28''$ from the radio position of [19], improving significantly upon the previous optical position by the same authors. The difference between the centroids of the optical and *Chandra* positions of SN 1978K is $0.69''$ ($\alpha_{opt} - \alpha_X$ = -0.085s, $\delta_{opt} - \delta_X$ = -0.47$''$). Although this difference is small and comparable with the statistical errors, we decided to apply this correction to the *Chandra* position of NGC 1313 X-2 to eliminate any systematic error between the optical and X-ray astrometric calibrations. The resulting *Chandra* position of NGC 1313 X-2 is reported in Table 1.

The photometry of the objects in our optical image was performed calibrating the frame with the *R*-band magnitudes of 23 field stars from the SuperCosmos Sky Survey. The internal accuracy

observations and differ in part from those originally presented at the Meeting.

Table 1
Positions of NGC1313 X-2 and positions and optical magnitudes of field objects.

Observatory/Instr.	Object[a]	RA[J2000]	DEC[J2000]	R magnitude	Ref.
ROSAT/HRI	NGC1313 X-2	03 18 22.00±0.50	-66 36 02.3±3.0	–	[20]
XMM/EPIC-MOS	NGC1313 X-2	03 18 22.34±0.33	-66 36 03.7±2.0	–	[15]
Chandra/ACIS-S	NGC1313 X-2	03 18 22.18±0.12	-66 36 03.3±0.7	–	this work
ESO/3.6m	A	03 18 21.97±0.05	-66 36 06.5±0.3	19.8±0.2	this work
ESO/3.6m	B	03 18 21.56±0.05	-66 36 00.9±0.3	20.7±0.2	this work
ESO/3.6m	C	03 18 22.34±0.05	-66 36 03.7±0.3	21.6±0.2	this work
ESO/3.6m	D	03 18 20.96±0.05	-66 36 03.7±0.3	17.8±0.2	this work

[a] See Figure 1.

of this calibration procedure is 0.2 mag at 1-σ. The magnitudes of the relevant objects in the field are reported in Table 1. The measurement for object D is in good agreement with the value in the SuperCosmos Sky Survey catalog.

3. DISCUSSION

The shifted *Chandra* position of NGC1313 X-2, corrected to match the optical and X-ray positions of SN 1978K, is shown in Figure 1, together with the *ROSAT* HRI [20] and *XMM* EPIC-MOS [15] error boxes, overlaid on our ESO image. All measurements are consistent within 1-σ. The distance of the centroids of objects A, B and D with respect to the (shifted) *Chandra* position is 3.6″, 4.1″ and 7.3″, respectively. Even taking into account the statistical error on the optical positions (0.3″), these three objects can be ruled out at a significance level of at least 3-σ. On the other hand, object C is inside the Chandra error box and its position coincides within 1-σ with that of NGC 1313 X-2, making it a likely counterpart.

From the maximum absorbed X-ray flux of NGC 1313 X-2 ($f_X = 2 \times 10^{-12}$ erg cm^{-2} s^{-1}) and optical magnitude of object C ($R = 21.6$), we estimate $f_X/f_{opt} \sim 500$. Only Isolated Neutron Stars (INSs), heavily obscured AGNs and luminous X-ray binaries can reach such large values of the X-ray/optical flux ratio. INSs are extreme in this respect, with B$\approx$ 25 optical counterparts and typical X-ray-to-optical flux ratios $\geq 10^5$ (see e.g. [14,11] for the counterparts of Anomalous X-ray Pulsars). The presence of object C in the *Chandra* error box makes this possibility unlikely. Furthermore, known INSs exhibit different spectral properties with no significant variability. On the other hand, a heavily obscured AGN is expected to have a rather hard X-ray spectrum and to emit significantly in the near-infrared (see e.g. [2]). Since NGC 1313 X-2 is relatively bright in X-rays, infrared emission would be expected at a higher level ($K \approx 12$), were it an obscured AGN. The lack of any IR counterpart on a K image of the 2MASS All Sky Image Service down to a limiting magnitude $K \simeq 14$ (10-σ) and the softer X-ray spectrum of NGC 1313 X-2 rule out this possibility. Our accurate *Chandra* position and optical identification essentially leave only a very luminous X-ray binary in NGC 1313 as a viable option for NGC 1313 X-2. This is in line with the binary nature of ULXs and is consistent with the observed properties of this source, such as the X-ray variability and the observed X-ray spectrum, including the presence of a soft component probably produced by an accretion disk [15].

If indeed NGC 1313 X-2 is a black hole binary, the X-ray spectral parameters, in particular the temperature and/or the normalization of the soft component can be used to estimate the BH mass, as already done by Miller et al. [15]. Fitting the soft component with a multicolor disk (MCD) blackbody model, they find that NGC1313 X-2 contains an intermediate mass BH with a mass in excess of $100 M_\odot$. The large inferred BH mass does not require beamed emission. Then, the estimated accretion rate (assuming 10% efficiency)

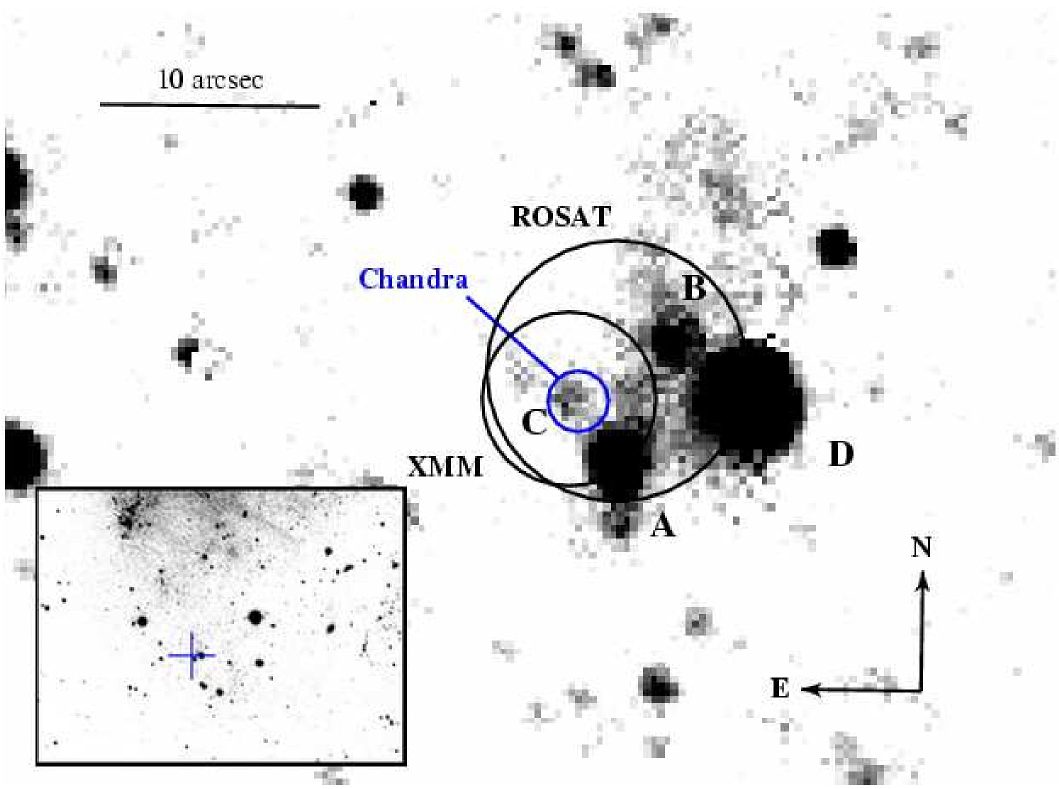

Figure 1. ESO 3.6m R-band (Bessel filter) image of the field of NGC1313 X-2. The circles show the *ROSAT* HRI, *XMM* EPIC-MOS and *Chandra* ACIS-S positions. The estimated 90% confidence radii are $6''$ for HRI, $4''$ for EPIC-MOS and $1.4''$ for ACIS-S. Labels A, B, C and D mark the four field objects inside or close to the X-ray error boxes. The insert at the bottom-left shows a larger portion of the image with the position of the X-ray source (*cross*).

is $\dot{M} \approx 10^{-7}\, M_\odot\, \mathrm{yr}^{-1}$, forcing the mass reservoir to be a companion star.

From the apparent magnitude of object C ($R = 21.6$) and its visual absorption ($A_R \simeq 1.6$, computed from the X-ray best fitting column density $N_H \sim 3{\times}10^{21}\ \mathrm{cm}^{-2}$ [1]), we estimate a luminosity $\approx 10^5 L_\odot$, depending on the adopted bolometric correction. If this originates from the companion star, the inferred luminosity is consistent with a $\approx 10 M_\odot$ supergiant, making NGC 1313 X-2 a high-mass X-ray binary. Assuming that 20–30% of the X-ray flux produced in the innermost part of the accretion disk intercepts the outer regions, for realistic values of the albedo (≥ 0.9, e.g. [6]), few percents of the X-ray luminosity ($\approx 10^{38}$ erg s^{-1}) can be absorbed and re-emitted in the optical band. Characteristic emission lines of X-ray-ionized H, He or N, typically seen in luminous Galactic X-ray binaries should then be detectable in the optical spectrum. Also X-ray heating of the companion star itself may contribute to the optical emission. We can not rule out also that the optical emission detected in the *Chandra* error box originates from a stellar cluster (see e.g. the case of a ULX in NGC 4565 [22]), in which case NGC 1313 X-2 might be a low-mass X-ray

binary in the cluster.

The mass accretion rate required to power the observed luminosity may in principle be provided by Roche-lobe overflow from an evolved companion or a wind from a supergiant. In the first case, evolutionary swelling of the companion keeps pace with the increase in Roche lobe size and the system remains self-sustained: accretion is likely to proceed through a disk. In the second case, assuming 10% accretion efficiency and that the BH can capture $\sim 1\%$ of the mass outflow, the wind must be very powerful ($\dot{M} \sim 10^{-5}\, M_{\odot}\, \mathrm{yr}^{-1}$). A lower efficiency would require too high a gas supply, making a disk needed even for a wind-fed system. The disk would probably be much smaller than in a Roche-lobe overflow system and the optical emission dominated by the supergiant. On the other hand, in a Roche-lobe overflow system, an extended, possibly re-irradiated accretion disk should contribute heavily in the UV and B bands, producing strong emission lines.

A crucial question is how a binary system containing an intermediate mass BH may have formed. The BH progenitor must have been rather massive. This is consistent with the fact that NGC 1313 is likely to have a low metallicity ($Z \sim 0.1 - 0.2$ [18]). Such a massive BH may have formed through direct collapse without producing a supernova. In this way, if the system was born as a binary, it may have survived after the collapse of the primary. Although less likely, it is also possible that the companion might have been captured from a nearby stellar association. In this case, it is not possible to exclude that the BH may have formed from an early episode of star formation (population III).

It is worth noting that, although the large BH mass does not require that the emission is beamed, we cannot rule out that a moderate jet activity, producing radio emission, is present in NGC 1313 X-2 (see e.g. the case of an ULX in NGC 5408 [13]). However, presently available radio images of the field of NGC 1313 X-2 (Sydney University Molonglo Sky Survey at 843 MHz and Australia Telescope Array at ~ 5 GHz [21]) are not sufficiently deep to allow detection.

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